Hadronic dissipative effects on transverse dynamics at RHIC

T Hirano[1], U Heinz[2,3], D Kharzeev[4], R Lacey[5] and Y Nara[6]

[1]Department of Physics, The University of Tokyo, Tokyo 113-0033, Japan
[2]Department of Physics, The Ohio State University, Columbus, OH 43210, USA
[3]CERN, Physics Department, Theory Division, CH-1211 Geneva 23, Switzerland
[4]Nuclear Theory Group, Physics Department, Brookhaven National Laboratory, Upton, NY 11973-5000, USA
[5]Department of Chemistry, SUNY Stony Brook, Stony Brook, NY 11794-3400, USA
[6]Akita International University, Akita 010-1211, Japan

E-mail: hirano@phys.s.u-tokyo.ac.jp

Abstract. We simulate the dynamics of Au+Au collisions at the Relativistic Heavy Ion Collider (RHIC) with a hybrid model that treats the quark-gluon plasma macroscopically as an ideal fluid, but models the hadron resonance gas microscopically using a hadronic cascade. We find that much of the mass-ordering pattern for $v_2(p_T)$ observed at RHIC is generated during the hadronic stage due to build-up of additional radial flow. We also find that the mass-ordering pattern is violated for ϕ meson due to small interaction cross section in the hadron resonance gas.

1. Introduction

Whether the quark-gluon plasma (QGP) behaves like a "perfect liquid" is one of the important question in heavy ion collisions at the Relativistic Heavy Ion Collider (RHIC) [1, 2, 3, 4]. The observed elliptic flow parameter v_2 and its transverse momentum dependence agree well with predictions from ideal fluid dynamics assuming zero viscosity [5, 6]. The ideal fluid dynamical description, however, gradually breaks down as one studies peripheral collisions or moves away from midrapidity [5, 6]. This requires a more realistic treatment of the early and late stages in dynamical modeling of relativistic heavy ion collisions. In previous work [7, 8] we have shown that a large fraction of these deviations from ideal hydrodynamics is due to "late viscosity". Here we report additional results from the hybrid model study focusing our attention on a detailed investigation of dissipative effects during the late hadronic rescattering stage.

2. Model

For the space-time evolution of the perfect QGP fluid we solve numerically the equations of motion of ideal fluid dynamics for a given initial state in three spatial dimensions

and in time [9, 10]. For the high temperature ($T > T_{\rm c} = 170$ MeV) QGP phase we use the equation of state of massless parton gas (u, d, s quarks and gluons) with a bag pressure B. We switch from ideal hydrodynamics to a hadronic cascade model at the switching temperature $T_{\rm sw} = 169\,\text{MeV}$. The subsequent hadronic rescattering cascade is modeled by JAM [11], initialized with hadrons distributed according to the hydrodynamic model output, calculated with the Cooper-Frye formula [12] along the $T_{\rm sw} = 169\,\text{MeV}$ hypersurface. JAM implements experimental hadronic scattering cross section data where available and uses the additive quark model where data do not exist, assuming the following formula for the total cross section [11, 13, 14, 15]:

$$\sigma_{\rm tot} = \sigma_{NN}^{\rm tot}\frac{n_1}{3}\frac{n_2}{3}\left(1 - 0.4\frac{n_{s1}}{n_1}\right)\left(1 - 0.4\frac{n_{s2}}{n_2}\right). \tag{1}$$

Here $\sigma_{NN}^{\rm tot}$ is the total nucleon-nucleon cross section, n_i is the number of constituent quarks in a hadron and n_{si} is the number of strange quarks in a hadron. For hadrons composed entirely of strange quarks, such as $\phi = (s\bar{s})$ and $\Omega = (sss)$, the cross sections become very small due to the suppression factors in brackets in Eq. (1). We note that, to study ϕ mesons in our hybrid model, we stabilize them by turning off their decay channels during the hadronic cascade. For initial conditions in hydrodynamic equations, we employ the Glauber model suitably generalized to account for the longitudinal structure of particle multiplicity [7, 16].

3. Results

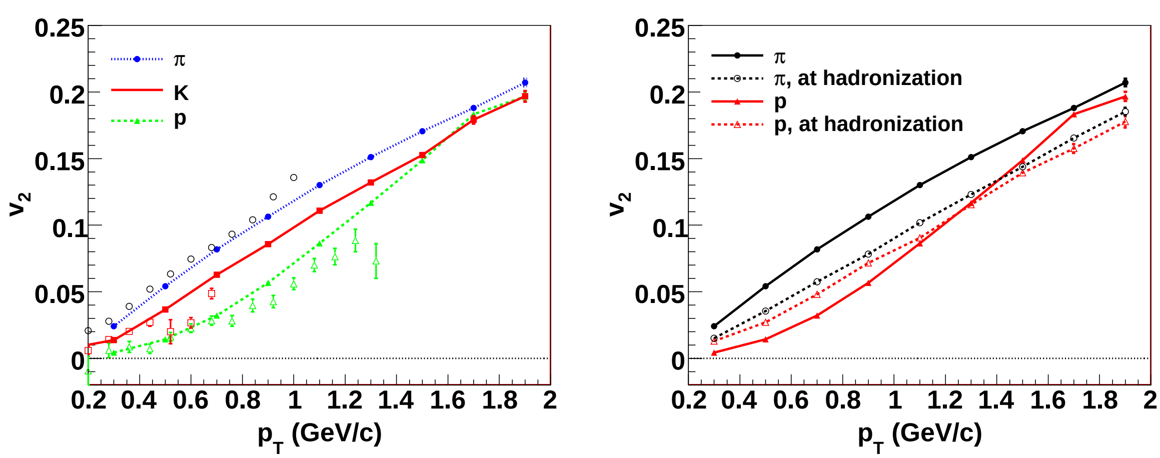

Figure 1. Transverse momentum dependence of the elliptic flow parameter $v_2(p_{\rm T})$. (Left) $v_2(p_{\rm T})$ for pions, kaons and protons from the hybrid model are compared with STAR data [17]. (Right) Solid (dashed) lines are with (without) hadronic rescattering.

In Fig. 1 (left), we compare $v_2(p_{\rm T})$ for pions, kaons and protons from the hybrid model with the STAR data [17]. We reasonably reproduce mass-splitting behaviour seen in the data. We note that we also reproduce the data in other centralities (not shown) except for very central collisions due to absence of eccentricity fluctuation [18]. Figure

1 (right) shows how mass-splitting of $v_2(p_{\rm T})$ is generated during evolution by switching off hadronic rescatterings in a hadronic cascade. Slope of pion $v_2(p_{\rm T})$ becomes steeper due to additional development of elliptic flow and reduction of mean $p_{\rm T}$ [19]. For heavy hadrons, on the other hand, radial flow reduces v_2 at low p_T [20]. Assuming positive elliptic flow, $v_\perp(\varphi{=}0,\pi) > v_\perp\left(\varphi{=}\frac{\pi}{2},\frac{3\pi}{2}\right)$, the stronger transverse flow $v_\perp$ in the reaction plane pushes heavy particles to larger $p_{\rm T}$ more efficiently in the reaction plane than perpendicular to it. The generation of additional radial flow *in the hadronic stage* is responsible for the mass-splitting of $v_2(p_{\rm T})$ observed in the low $p_{\rm T}$ region. From these observations we conclude that the large magnitude of the integrated v_2 and the strong mass ordering of $v_2(p_{\rm T})$ observed at RHIC result from a subtle interplay between perfect fluid dynamics of the early QGP stage and dissipative dynamics of the late hadronic stage.

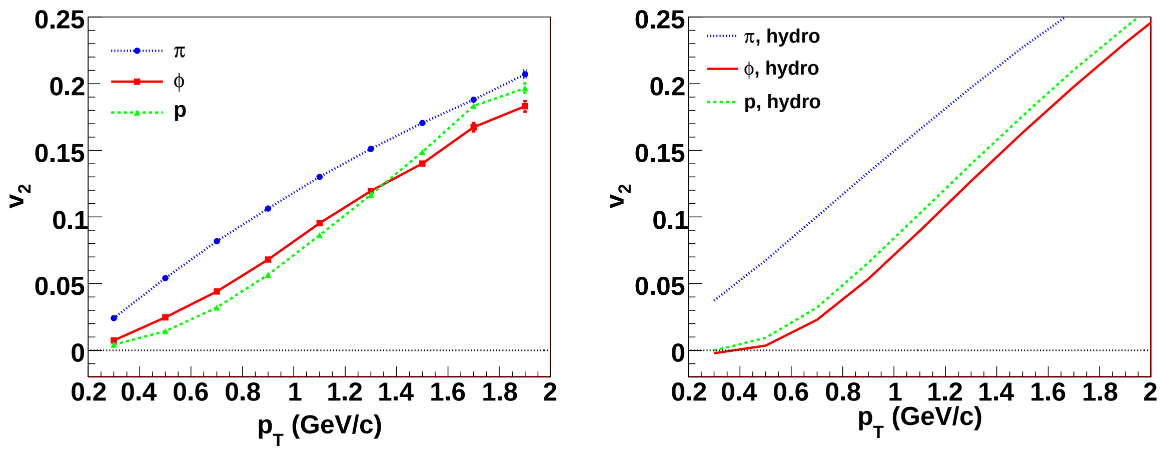

Figure 2. (Left) $v_2(p_{\rm T})$ from the hybrid model. (Right) $v_2(p_{\rm T})$ from ideal hydrodynamics with $T^{\rm dec}$=100 MeV. Solid, dashed and dotted lines are results for ϕ mesons, pions and protons.

ϕ mesons have considerably smaller scattering cross sections than non-strange hadrons [21]. They are therefore expected to show larger dissipative effects in our hybrid model and not to fully participate in the additional radial flow generated during the hadronic rescattering stage. Figure 2 shows $v_2(p_{\rm T})$ from the hybrid model (left) and the ideal hydrodynamics (right) for π, p and ϕ. As a result of rescattering the proton elliptic flow ends up being smaller than that of the ϕ meson, $v_2^p(p_T) < v_2^\phi(p_T)$ for $0 < p_T < 1.2\,{\rm GeV}/c$, even though $m_\phi > m_p$. The large cross section difference between the protons and ϕ mesons in the hadronic rescattering phase leads to a violation of the hydrodynamic mass ordering at low $p_{\rm T}$ in the final state.

4. Summary

We have studied effects of hadronic dissipation on differential elliptic flow in Au+Au collisions at RHIC, using a hybrid model which treats the early QGP phase

macroscopically as a perfect fluid and the late hadronic phase microscopically with a hadronic cascade. The well-known mass-splitting of the differential elliptic flow observed in hydrodynamic models is seen to be mostly generated during the hadronic rescattering phase and to be largely due to a *redistribution* of the momentum anisotropy built up during the QGP stage. This redistribution is caused by the mass-dependent flattening of the transverse momentum spectra by additional radial flow generated during the hadronic stage. The much more weakly interacting ϕ mesons do not participate in this additional radial flow and thus are not affected by this redistribution of momentum anisotropies: their differential elliptic flow remains almost unaffected by hadronic rescattering. The net result of dissipative hadronic rescattering is therefore that the differential elliptic flow of protons *drops below* that of the ϕ mesons, in violation of the hydrodynamic mass-ordering.

Acknowledgments

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